Istanbul Strait Road Tube Crossing: Challenges, Risks and Mitigation Strategies

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ABSTRACT

The 13.2 m external diameter double deck Istanbul Strait Road Tube Crossing is one of the most challenging underwater tunnel projects in the world. Subjected to 11 bars of hydrostatic pressure, variable geology, and being in a very active seismic area, the execution of the project required innovative solutions, sophisticated construction techniques, and prudent risk management approach. The 5 km tunnel consists of 3.4 km TBM bored tunnel, 1 km twin NATM tunnels, and cut and cover sections. The project is being delivered in a Build-Operate-Transfer (BOT) contract in a public-private partnership. The technical challenges, coupled with financial and commercial risks required the implementation of sophisticated risk management tactics including the provision of Independent Design Verification. Presently, the project is in its advanced stages of construction with a recent successful TBM breakthrough on August 22nd 2015. The paper presents the technical challenges of the project from the design, construction, and risk management aspects and provides the status of the construction.

PROJECT BACKGROUND

The $1.245 billion Istanbul Strait Road Tunnel Crossing project, dubbed the Eurasia Tunnel, is one of several major infrastructure projects being implemented in the Republic of Turkey in a public-private partnership approach. The project provides a direct and easy connection between the Anatolian (Asian) side of Istanbul and the heart of its historical district on the European side across the Bosphorus Strait which connects the Black Sea with the Sea of Marmara. Upon its completion in 2017, the project will improve connections to a wide network of motorways on both sides, increase capacity across the Bosphorus by 100,000 vehicles a day, reduce congestion and save motorists an average of 45 minutes of commuting time in each direction, and bringing significant economic benefits to the city and the region; it will ease traffic across the strait, reduce congestion, decrease pollutants and emission while maintaining the historical silhouette of the city. Figure 1 provides a general view of the project location and alignment. The overall project consists of three parts totaling 14.6km. Parts 1 and 3 consist mainly of widening existing motorways, providing connections to existing roads, reconstructing local bridges and underpasses on the European and Anatolian sides respectively. Part 2 is the tunnel crossing across the Bosphorus; it is the most complex part of the project with the greatest challenges and risks. Part 2 is 5.4 km long consisting of 3.4 km of 13.2m external diameter TBM bored tunnel under the Bosphorus Strait, 1-km of twin NATM tunnels on the Asian side, cut and cover transition boxes in the Asian and the European sides and depressed approaches on both sides. In addition, this segment includes the toll plazas, ventilation buildings, and the tunnel control and maintenance facilities.

Figure 1 – Project Alignment

Public-Private Partnership Achieves Successful Execution of Needed Infrastructures

The Employer, the Ministry of Transport, Maritime Affairs and Communications, and Directorate General of Infrastructure Investments (AYGM) selected ATAŞ (Avrasya Tüneli İşletme İnşaat ve Yatırım A.Ş.), a joint venture of the distinguished Turkish firm Yapı Merkezi (YM), and the experienced Korean firm of SK Engineering and Construction Co. Ltd. (SK E&C) as the project Concessionaire to build and operate the facility for a concession period of 26 years. Each of these two firms is well-known for their successes in large-scale infrastructure and transportation projects in their respective market sectors. With a total investment of $1.245B of which about $300M is in equity, ATAŞ is committed to start the tunnel operation within 48 months from the financial closure. The project financial closure took

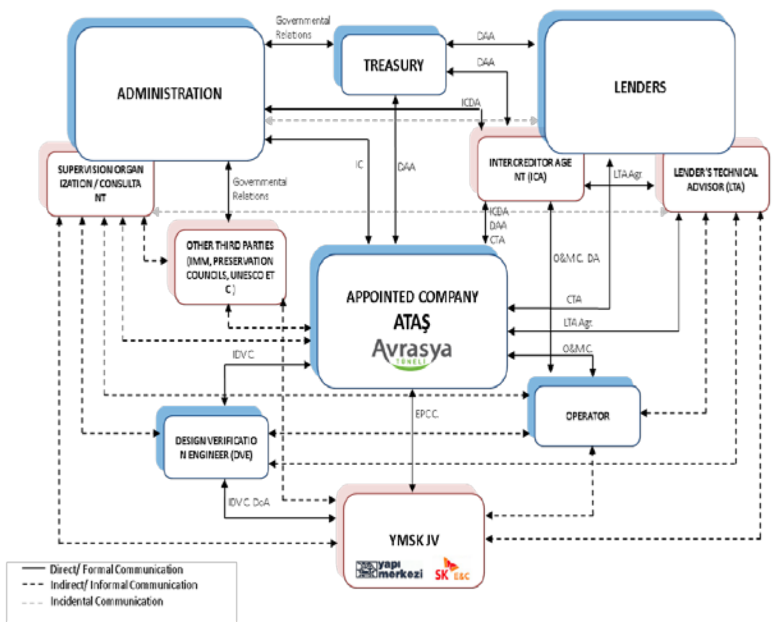

Figure 2 shows the project stakeholders relationships.

place in March 2013 and the tunnel operation is anticipated to start in March 2017.

To implement the project ATAŞ assigned the Joint Venture of Yapi Merkezi and SK E&C (YMSKJV) to design and construct the project. A global team of top engineering firms were assembled to tackle this unique and challenging project including Parsons Brinkerhoff as the lead designer, HNTB as the Independent Design Verifier (IDV), Fugro for the geotechnical studies, Herrenknecht as the TBM supplier, Yapı Merkezi Prefabrication as the segment producer, and Egis as the facility operator among many other local and international firms.

PROJECT CONFIGURATION MEETS THE GEOLOGICAL SETTING

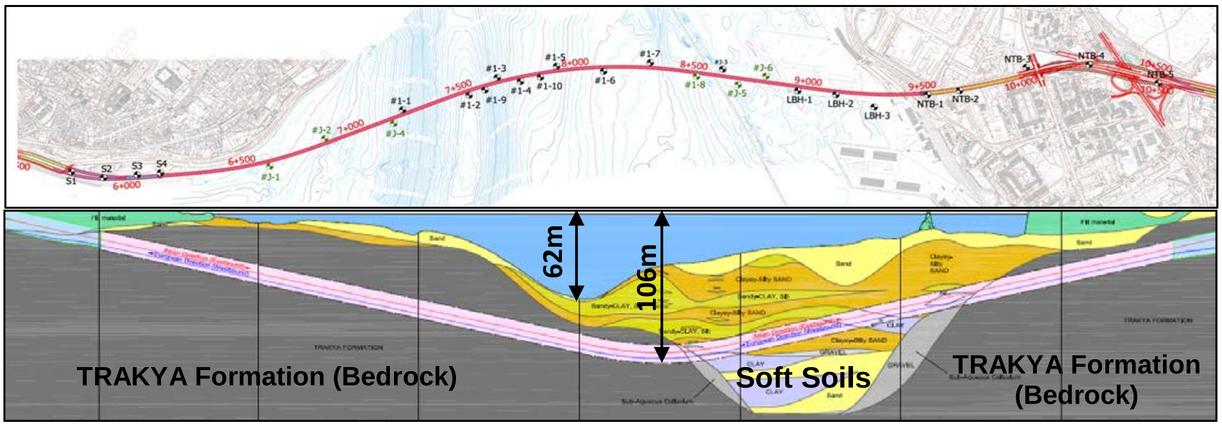

Figure 3 – Tunnel Plan and Profile

The sub-sea single TBM tunnel passes through weathered bedrock (Trakya Formation) on either side of the Istanbul Strait and through alluvial deposits including sand and gravel near mid channel. The TBM tunnel was bored to a depth of 106 m below the water surface requiring it to resist 11 bars of hydrostatic pressure and up to 22 bars of hydrodynamic pressure during a severe earthquake. The stacked tunnel transitions on the Asian side in the Asian Transition Box, a cut and cover structure, to twin NATM tunnels approximately 1-km long each excavated in the Trakya formation. The bored stacked tunnel transitions to two cut and cover tunnels in the European Transition Box. Tunnel portals on either side were constructed using cut-and-cover methods in alluvium soils and total about 1-km in length. The tunnel plan and profile are shown in Figure 3.

Bored Tunnel Cross Section

The TBM bored tunnel was designed with stacked roadways that included emergency walkway and emergency alcoves. Figure 4 illustrates the layout of the stacked roadways in the TBM bored tunnel. The tunnel nominal outside diameter of 13.2m and 12.0m inside diameter provided space for two 3m wide travel lanes in each direction and a 1.2 m wide emergency egress at each level. The 3m vertical clearance allowed for cars, vans, and mini busses only. Emergency egress stairways were provided every 200m into pressurized stairwells connecting the upper and lower roadways; and vehicular breakdown alcoves were provided every 600m. Longitudinal ventilation was provided by jet fans in the ceiling of each roadway supplemented by two ventilation buildings. In addition, all other essential elements including traffic control, lighting, communication, etc. were provided in each traffic level. The upper roadway was cast in situ and supported by cast in situ concrete corbels on either side that are anchored into the precast segmental tunnel lining thru the use of grouted steel dowels. The lower roadway deck was formed with precast concrete panels resting on similar corbels. The space beneath the lower deck accommodated the cableways, sump pumps, water and drainage systems, and other utilities supporting the tunnel operation.

The tunnel was constructed using concrete precast segmental liner 600mm thick, 2 m long double reinforced with a compressive strength of 50 MPa and equipped with double 37mm EPDM gaskets. Each ring consisted of eight segments and a key. The individual segments were connected using spear bolts in the circumferential and the longitudinal joints. Guide rods were used between rings to assist ring build accuracy. Cam and sockets were included on circumferential joints to assist in achieving ring-build accuracy and to provide supplementary support for segments during the ring building operation.

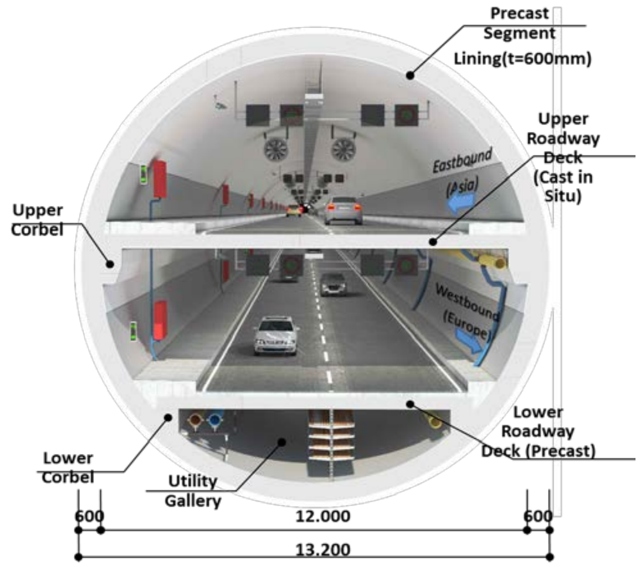

Figure 4 – Bored Tunnel

NATM Section

The NATM section provides a connection between the Asian Transition Box and east portals extending 930 m. The twin NATM tunnel cross section has a typical curvilinear configuration including the invert due to poor ground conditions and the high hydrostatic pressure. See Figure 5. The two NATM tunnels are very close to each other with a limited pillar on the western end, but they diverge as they extend eastward. The twin NATM tunnels include four cross passages, a lay-by area for disabled vehicles and four mechanical and electrical rooms. The construction of the NATM tunnels was done by top heading, bench, and invert using pre-support arch canopy to deal with the poor ground conditions. Near the portals, the cover over the tunnels is limited requiring special pre-support measures and rigorous monitoring. The initial liner consisted of 200mm shotcrete over lattice girders and rock bolts. The final liner is cast in situ 400mm reinforced concrete over fully encapsulated PVC waterproofing membrane system.

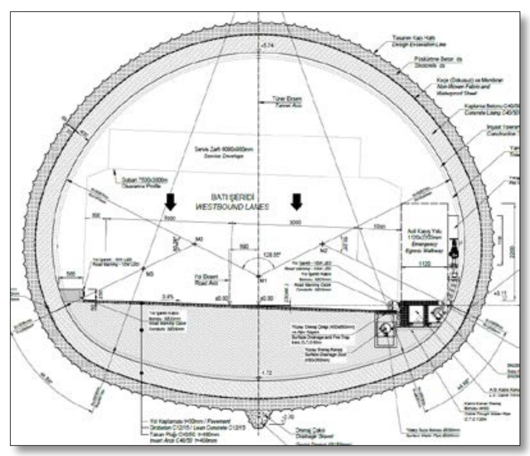

Figure 5 – NATM Tunnel Cross Section

GEOTECHNICAL INVESTIGATIONS DEFINE SUBSURFACE CONDITIONS

The bedrock underlying the tunnel alignment is the Trakya Formation, a sedimentary rock composed of inter-layered siltstones/mudstones and sandstones. Generally, there are three primary joint sets in the Trakya, with the siltstone/mudstone exhibiting additional random jointing not observed in the sandstone. One joint set is approximately horizontal and the other two are oriented approximately orthogonal in a NW-SE and a NE-SW direction. The dip angle of the latter two joint sets is relatively steep, varying from approximately 65° to 85°.

The sedimentary rock of the Trakya formation has been intruded by igneous dykes of diabase, andesite, or dacite. Based on observations at the adjacent Marmaray rail tunnel project, the igneous dykes occur at a frequency of approximately 70 to 150m with variable thickness up to 20m. The rock adjacent to the intrusive dykes is more intensely fractured and weathered than the unaltered bedrock. Soft ground is alluvial deposits ranging from coarse-grained soils (gravels and sands) to fine-grained soils (silts and clays) and can vary both vertically and laterally as a result of depositional history. The TBM tunnel passes through mostly silty fine sand and some clay and sandy clay layers. Gravel and cobbles are encountered at the interfaces between the Trakya formation and the alluvial soils. Figure 3 shows the geological stratigraphy.

The geotechnical investigations included 17 offshore borings taking undisturbed tube samples in soil and core samples, RQD, and drilling rates recorded in rock. Several offshore borings included sonic logging to determine dynamic properties of the soil and rock. Offshore investigations also included a 3-D high-resolution shallow seismic geophysical survey, extending from approximately 50 to 100 m to either side of the tunnel alignment to define soil stratification and top of rock surface along the crossing. Extensive laboratory and in-situ testing was performed including hardness tests, abrasion tests, slake durability tests, and P and S wave velocity determinations, among others.

Seismic Conditions

Istanbul Metropolitan area falls within three tectonic plates: the African, the Anatolian, and the Eurasian plates. The collisions of these plates have resulted in the formation of complex fault systems in the area with the Marmara fault being the most prominent and most active. The project site lies about 16 km from the Marmara fault as shown in Figure 6, therefore a thorough assessment of the risks associated with a potential earthquake is very important for the safety of the tunnel. To address the high seismic risk, the Employer specified a performance based design earthquake approach using a Functional Evaluation Earthquake (FEE) with a 20% probability; and a Safety Evaluation Earthquake (SEE) with 4% probability of occurrence during the 100-year design life of the tunnel. The FEE and SEE generally correspond to design seismic events with return periods of 500 and 2,500 years respectively. The project-specific seismic hazard assessment defines the design earthquake magnitude as 7.25 (moment magnitude) and source-to-site distance as 16 km for both SEE and FEE. Under the SEE earthquake, life safety should be ensured and continuous operation of the facility with slight to no damage to structures; while for the FEE earthquake, life safety should be ensured and any structural damage should be repairable within a reasonable period.

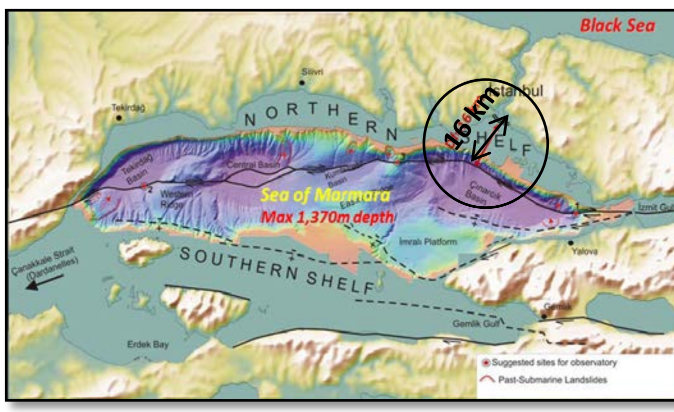

Figure 6 – Close proximity of the project site to the Marmara Fault increases the risk of seismic impact

BEST PRACTICES PROVIDE GOOD RISK MANAGEMENT

The project variable geology, hydrology, and susceptibility for high seismic activity combined with high water pressure and the large diameter/double-deck configuration make the Eurasia Tunnel one of today's most challenging and complex tunneling projects in the world. To address and mitigate the various risks, ATAS implemented a pro-active risk management plan from the initial design development stage through final design and construction. An essential element of the plan was the implementation of an independent design verification process. HNTB Corp. was retained by ATAS to perform this function and to provide technical support and advice to the project team throughout the Basic and the Detailed design phases and during construction.

Independent Design Verification (IDV) Process

As part of the independent verification process, detailed reviews and independent analyses and checks were performed for category 3 structures (per Eurocode) and for all other critical elements of the project. To assure quality performance and to mitigate potential risks, the independent verification was extended to cover all other major elements and disciplines including verification of the tunnel alignment, the tunnel major mechanical and electrical systems and services including power, lighting, hydraulics, tunnel ventilation, fire life safety, communications, architectural and space planning, traffic control, and system integrations, as well as facility operation. The goal was to verify compliance with Employer's requirements and with design codes and standards. Furthermore, the IDV reviews included potential value engineering ideas and betterments to improve construction cost and/or schedule.

The verification of the Basic Design assured that the design was brought to a sufficient level of completion to enable YMSKJV and the Employer to evaluate the inherent risks. In the Detailed Design, the final calculations, drawings and technical specifications were verified. The independent verification included independent calculations for most critical components including the bored tunnel, seismic analyses, NATM tunnels, transition structures, cut and cover tunnels, retaining walls, U-sections, portals, temporary support of excavation, systems and buildings, ventilation analyses, and alignment and drainage calculations. The IDV reviews have determined that the design complies with Employer's requirements and design criteria, met codes and standards, reduced construction risks, improved constructability, increased safety and efficiency of the facilities, and decreased operational costs. The IDV role also addressed project risk elements and recommended solutions/approaches to mitigate design related risks. After both the Basic and the Detailed Designs were verified, a Design Verification Certificates (DVC) were issued allowing YMSKJV to proceed with the construction of the verified packages and to obtain the Employer's and Lenders' approvals. The role of the IDV provided ATAS the mechanism for self-certification, provided the Employer assurances that the design meets its requirements and the project codes and criteria, and provided the lenders affirmation that the design meets its intended purpose and its requirements in support of their financial investments. This approach reduced potential risks to ATAS, to the Employer, and to the lenders.

TECHNICAL CHALLENGES AND RISKS MITIGATED BY THE APPLICATION OF STATE-OF-THE-ART TECHNOLOGY

The following are the project's most critical technical challenges that required special attention of the design, the construction, and the independent design verification teams. Risks associated with these challenges were identified early and mitigation measures were implemented during the design and the construction in order to manage them.

The main project risks included the large tunnel diameter, the high hydrostatic pressure, the variable and difficult ground conditions, and the high seismic loading. To address some of these risks, a state of the art Herrenknecht's Mixshield TBM was specifically designed for the project. The TBM was designed to be capable to address the various ground conditions encountered and the high hydrostatic pressure as will be discussed herein below. Figure 7 shows the project TBM. It is 13.71m in diameter, 120m long, and weighs 3,300 tons. It is designed to handle 12 bar of water pressure and to deal with variable and mixed ground conditions.

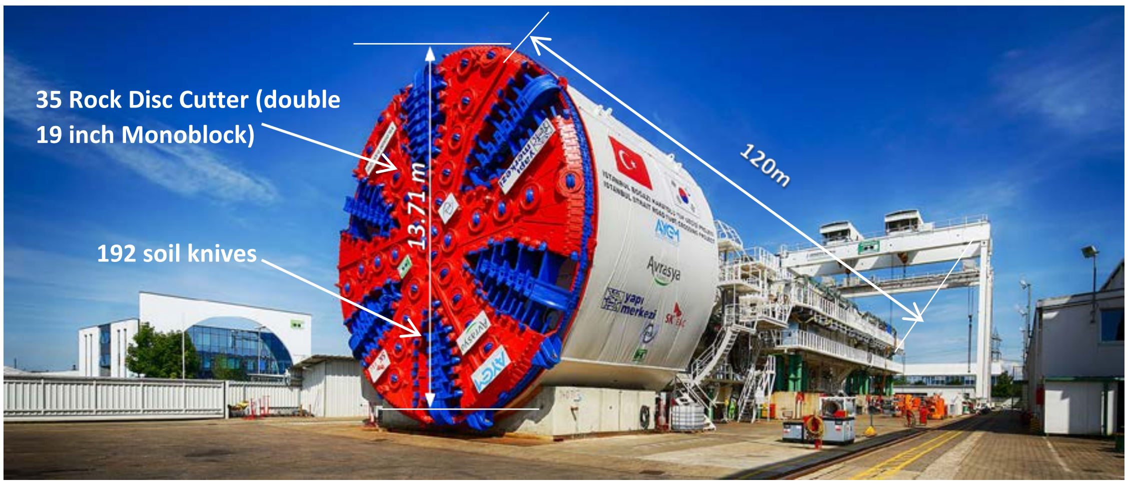

Figure 7 – Eurasia tunnel TBM was designed to handle high water pressure and difficult ground conditions

Due to the high hydrostatic pressure, the TBM was designed to allow almost complete access to the back of the cutting wheel under atmospheric pressure. From there, all disc cutters and a large number of the soil cutting knives can be changed safely under atmospheric pressure. In addition, the TBM was equipped with air lock systems which allow access for compressed air works; furthermore, saturation diving using transfer shuttle if needed was provided.

The TBM design accommodated the high face pressure and the differential pressure between the crown and the invert. In addition, the tailskin seal system consisting of three rows of wire brush seals and an inflatable emergency seal allowed the grouting of the annular space from within the tail shield. During TBM advance, grease is pumped between the wire brushes with a pressure higher than the backfill grout injection pressure. This ensured a seal and maintained the face pressure.

Large Bore Tunnel

The Eurasia tunnel being the 6th largest tunnel in the world, by itself, is a challenge; however combining the large size of the tunnel with various other challenges stated above makes this tunnel construction to be one of the most challenging in the world. The tunnel cross section was developed in way to provide all needed functions in as compact arrangement as possible in order to reduce the overall diameter, yet accommodate all traffic and life safety elements. As indicated above, the design of the tunnel consisted of two traffic compartments each providing two standard lanes, and an emergency walkway. See Figure 3 above. Due to the tight geometrical configurations, the upper deck had to be constructed using cast in situ, while the lower deck will be constructed using precast units. In order to meet the overall project schedule, the construction of the interior structure progressed as the TBM tunneling was progressing.

Navigating in Difficult Ground Conditions

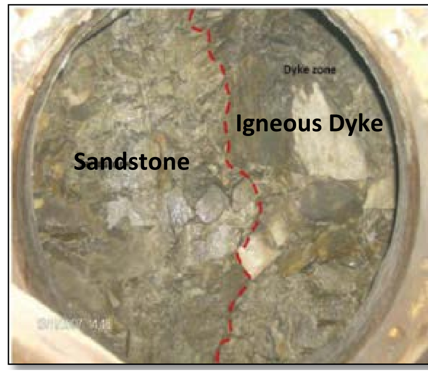

Figure 8 – Volcanic dyke in the Trakya based on Mamaray Tunnel experience

As discussed above, the project geology that the TBM had encountered generally consists of the Trakya bedrock formation underlying the alluvial sediments at the bottom of the channel. The Trakya formation consists of sedimentary rock of sandstone, mudstone, and siltstone. The formation of the strait was formed by historic tectonic forces which left the Trakya bedrock folded, faulted, intruded, intensely fractured and weathered. Within the Trakya formation, volcanic igneous dykes intrusions of diabase, andesite and dacite more than 100m thick were encountered resulting in the presence of highly variable rock strengths, abrasive mineralogy, and the presence of stiff blocks embedded in soft matrix. Figure 8 illustrates the presence of a volcanic dyke in the Trakya formation based on the nearby Marmaray tunnel project. In addition, faults at various locations across and adjacent to the tunnel alignment were encountered. The alluvial deposits varied from gravels and sands to silts and clays. Cobbles and boulders are also present in the soil matrix especially at the interface between the Trakya formation and the alluvial deposits. The TBM tunnel passes through mostly silty fine sand and some clay and sandy clay layers. Tunneling in mixed face conditions along the tunnel alignment was occurred in three potential geological situations: alluvial overburden materials overlying the Trakya Formation; interface between Trakya sedimentary bedrock and volcanic dyke intrusions, and fault zones passing through the Trakya. The top of rock varies in elevation as an undulating and inclined surface; therefore, the TBM was in and out of mixed face conditions for extended lengths.

The TBM was designed to deal with the variable ground conditions and the presence of volcanic dykes and boulders and cobbles. The TBM was equipped with 48 units of double 19” monoblock rock disc cutters in addition to 192 soil knives and a jaw crusher. The TBM operated in a closed face mode to control potential ground losses and to maintain face stability. Although abrasion did not present major problems, the high quartz content in the Trakya formation on the European side caused more frequent tool changes. The use of 19” discs improved the disc lives and their rigidity. The TBM was able to handle the presence of the igneous dykes and the boulder zones in the transition zones with no loss of slurry.

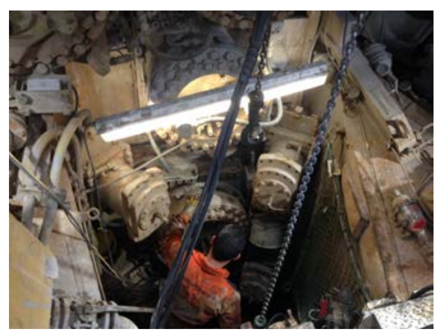

Figure 9 – Tool replacement under atmospheric pressure

Dealing with High Hydrostatic Head

The tunnel being subjected to 11 bars of water pressure requires special measures to be taken during construction and for the long term operation of the facility. Having such high water head and no ability to establish safe haven locations along the tunnel alignment, limited the ability of maintaining the TBM. Therefore as discussed above, the TBM was designed to allow all disc cutters and a large number of the cutting knives to be changed under atmospheric pressure. In addition, the TBM is equipped with an air lock system and saturation diving shuttle which allowed hyperbaric intervention as needed. It was reported that four hyperbaric interventions were implemented during the tunneling operation. Figure 9 shows tool replacement under atmospheric pressure.

To deal with the high water head for the 100 year design life of the tunnel, the liner was equipped with two 37mm EPDM gaskets on the intrados and the extrados to maintain water tightness during normal operation and in case of seismic movement.

Flexible Joints Accommodate Severe Seismic Potential

The bored tunnel passing through rock and alluvial deposits was analyzed for transverse, ovaling and longitudinal deformations due to seismic event. The transverse ground deformation analysis consisting of one-dimensional free-field site response analysis at different sections along the tunnel alignment was performed to derive ground deformation profiles and strain-compatible ground stiffness as input to the structural transverse analyses of the liner. The longitudinal tunnel and ground response analyses were performed using three-dimensional quasi-static beam-spring models. The three-dimensional free-field ground deformation-time histories evaluated from site-response analyses were applied at the support end of the ground springs to evaluate the tunnel-ground interaction. The strain compatible ground spring stiffness values were derived from quasi-static response analyses using a three-dimensional finite difference program. Figure 10 shows the results of the longitudinal forces. The results indicated that the placement of seismic joints at the interface between the rock and alluvial deposits reduces the seismic demands (axial force and transverse shear loads) to below the allowable levels. The seismic joints were designed with displacement capacity of ± 50 mm in shear offset and 75mm in extension/contraction. The seismic joints were designed, fabricated, and tested in Japan to meet the performance requirements including design life, durability, sustained loads, and water tightness. Figure 11 shows the model of the joint and in its final position.

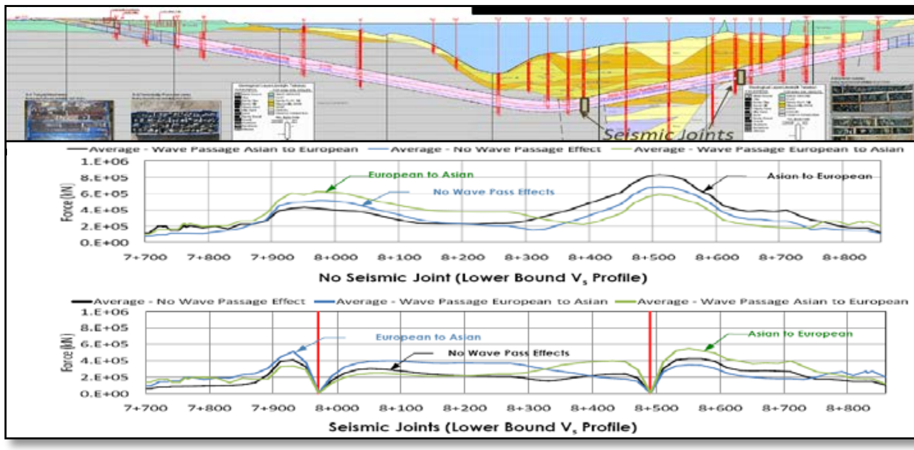

Figure 10 – Results of seismic analyses and locations of seismic joints

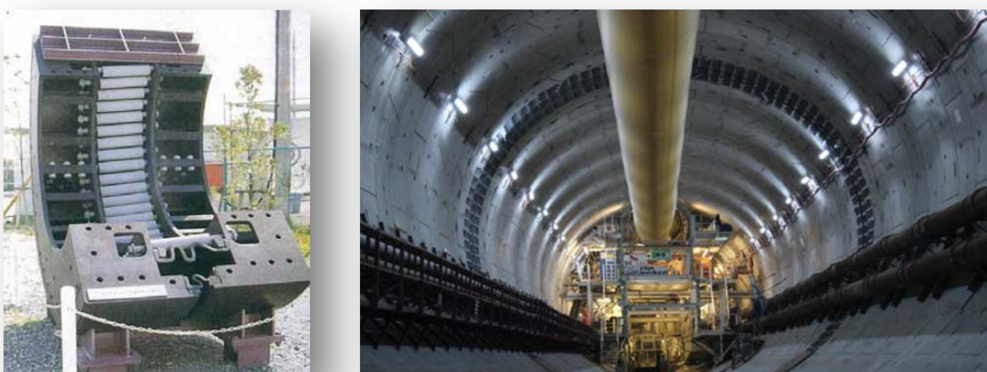

Figure 11 – Seismic Joint model and the joint in place

CONCLUSIONS

As of August 22nd 2015, the Eurasia tunnel project has completed the most challenging phases of its construction with the TBM breakthrough. Figure 12 shows the TBM breakthrough in the European transition box. All risk work elements involving various tunneling works were successfully completed ahead of their schedule. The project is planned to be completed and operational in March 2017.

Figure 12 – TBM breakthrough

It is proven that the project was set up from its very onset to incorporate multiple appropriate provisions to recognize, manage and mitigate construction and commercial risks. These provisions included the assembly of top level team, the inclusion of the IDV process, the selection of state of the art TBM, and the provision for risk management approach from the planning phase through construction and operation.

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